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13. ABSTRACT *(Maximum 200 words)*
A laboratory experimental program was carried out to investigate fundamental physical processes related to deep-ocean and under-ice convection occurring in high latitude oceans. With regard to deep convection, the aspects of interest were the preconditioning of a stratified region prior to the onset of convection, breakdown of stratification leading to turbulent convection, growth of convective layer against stable stratification, scales of convection, lateral processes leading to horizontal buoyancy exchanges and the final collapse of deep-convective regions. Studies on convection under an ice cap included the formation and melting of ice due to surface cooling of a two-layer stratified fluid. This problem is rich in a variety of physical processes such as double-diffusive transports of heat and salt and turbulent mixing across the pycnocline that separates the two layers. Important new mechanisms related to above-described convective processes were delineated and simple parameterizations were proposed to represent convective events in numerical models.

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STUDIES ON CONVECTION IN POLAR OCEANS

Final Report of the ONR Contract No.
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by

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1. Introduction:

During the contract period, the principal investigator H.J.S. Fernando, graduate student Michael Levy, undergraduate student Richard Eijmbert and post-doctoral associate Sergei Voropayev worked on several problems related to deep convection and ice formation in high latitude oceans. Several new phenomena were noted and useful parameterizations were developed during this project period. Results of the completed studies are outlined below. Relevant publications originated from the P.I.'s group during the contract period are listed at the end of this report.

Turbulent Convection from Isolated Sources

An experimental study was carried out to study the evolution of a turbulent buoyant plume in a homogeneous fluid. This study differs from many previous investigations carried out on point plumes, in that it considers finite diameter effects and the nature of flow near the source. The results have applications to a number of oceanic and atmospheric convective flows wherein typical horizontal extent of forcing D is much larger than the fluid layer depth. Experiments carried out with varying source diameters D and source buoyancy fluxes B_0, using the laser induced fluorescence and particle tracking velocimetry techniques for flow diagnostics, revealed the following:

(i) The initial development of the plume during the time $t < 1.2\left(D^2 / B_o\right)^{1/3}$ occurs as if the convection is horizontally homogeneous; i.e., the depth of the front grows as $h \approx 0.35(B_0 t^3)^{1/2}$, the lateral entrainment flow is insignificant and the frontal propagation occurs by the engulfment of ambient fluid by turbulent eddies. The entrainment flow could be detected at larger times t $>1.2\left(D^2 / B_o\right)^{1/3}$, especially after the plume underwent morphological changes and achieved a quasi-steady state at a time $t_e \approx 1.8\left(D^2 / B_o\right)^{1/3}$.

(ii) The plume under this steady state consists of two regions. In region I, $0 < z < z_c$, the plume width shrinks and achieves a minimum diameter of $b_m \approx 0.55D$ at a depth of $z_c \approx 0.28D$. In region II, $z > z_c$, the plume expands, much the same way as a point plume, and at larger z the source diameter effects fade away thus leaving B_0 and z as governing parameters.

(iii) Under quasi-steady conditions, the averaged maximum horizontal velocity in region I was found to be

$$V_x \approx 0.66\,(B_0 D)^{1/3},$$

and the vertical velocity in this region is proposed to have the dependence

$$W_c \approx 2.7(B_0 D)^{1/3}\left(\frac{z}{D}\right).$$

The instantaneous buoyancy within the plume shows high space-time variability but stable statistical averages can be discerned. For $z/D < 0.1$, the time-averaged buoyancy $\overline{b(r,z)}$, spatially averaged across the plume width at a given z, was found to be

$$\bar{b}_{av} \approx 10(B_0^2 / D)^{1/3}.$$

(iv) The mean centerline velocity and width averaged buoyancy measurements in region II showed the following for larger z/D values:

$$W_c \approx 1.2(B_0 z)^{1/3} \qquad \text{for } z/D > 0.3,$$

and

$$\bar{b}_{av} \approx 3.7\left(\frac{B_0^2}{z}\right)^{1/3}, \quad \text{for } z/D > 0.4,$$

indicating the absence of source diameter effects. These z dependencies have similarities to that observed in turbulent point plumes.

Experiments on the Doming of Isopycnals by an Upward Suction Velocity

A laboratory study was carried out to investigate the doming of the density interface of a two-layer fluid subjected to a localized upward suction velocity. The study was motivated by its possible application to the preconditioning phase of deep convection. The upward flow was induced by a rotating disk placed at the surface of the fluid system, which pumps fluid outward through the Ekman layer on the plate and induces an upward velocity near the center of the plate to compensate for the radial flow. It was found that the isopycnals are domed when the Richardson number Ri, based on the buoyancy jump across the interface Δb, the upper-layer depth H, and the

suction velocity w_e, $Ri = \Delta bH / w_e^2$, falls below a critical value of $Ri_c \approx 1.6x10^6$. As the doming increases, the density interface is increasingly exposed to the turbulence induced by the disk and to the secondary flows generated at the tank walls, thus causing the interface to recede.

Development of a Point Plume in the Presence of Background Rotation

An experimental study was carried out to investigate the evolution of a point plume in a rotating fluid. The plume delivers a specific buoyancy flux B at the surface of a homogeneous fluid layer of depth H subjected to a background rotation rate of Ω. The plume descends into the fluid layer, deflects at the bottom surface and then spreads horizontally. Depending on the experimental conditions, the plume can be affected by the background rotation either during its descending phase or the horizontal spreading phase. The present investigation was focused on the latter case, because of its strong geophysical relevance. The major findings of the study are:

(1) The initial descent of the plume occurs as if the background rotation is absent, and the time (t) growth laws for maximum plume width b_m and the vertical height h of the plume front were similar to that of non-rotating fluids; viz., $b_m \approx 0.38\left(Bt^3\right)^{1/4}$ and $h \approx 1.7\left(Bt^3\right)^{1/4}$. After traveling a distance $h_{c1} \approx 3.3 \left(B / \Omega^3\right)^{1/4}$ for a time $t_{c1} = 2.4\ \Omega^{-1}$, a measurable reduction of the descent rate could be observed because of the impeding influence of rotation on the lateral entrainment flow. The lateral growth of the plume is drastically reduced at the time of $t_{c2} \approx 5.5\ \Omega^{-1}$, possibly because of the influence of rotation on plume turbulence. Thereafter, the plume width remains at an approximately constant value of $b_c = 1.4 (B / \Omega^3)^{1/4}$ but the vertical descent continues until the plume impinges on the bottom of the tank.

(2) The entrainment flow into the plume is modified by background rotation so as to generate a cyclonic rim current in the upper layers surrounding the plume, which grows in thickness with time until it becomes barotropically unstable. The cyclonic circulation so generated have an average Rossby number of $u_m/2\Omega D_m \approx 0.3\text{-}0.5$, based on the maximum velocity

u_m and the corresponding diameter D_m. For $H < h_{c1}$ case, these instabilities are observed only after the plume descends to the bottom of the tank and breaks up into baroclinic eddies; see below.

(3) For the case $H < h_{c1}$, the plume reaches the bottom, deflects and spreads laterally. The lateral spreading of the deflected plume continues in an approximately axi-symmetric manner until the radius of the front becomes of the order as the Rossby deformation radius, whence the front is decelerated and is broken up to form anticyclonic eddies. As such, the observed instability appears to be baroclinic and, as stated above, preceded the instability of the upper-layer cyclonic flow. The wave number of vortices formed depended on the fluid depth H, in addition to the Rossby radius, signaling a strong interaction between upper and lower-layer vortices.

Although in our experiments the flow spread over the bottom surface, no stable baroclinic vortex was formed and the flow always disintegrated into several vortices. This is perhaps due to the energetic nature of the deflected flow, which possesses additional kinetic energy acquired during the plume descent, that can be used for baroclinic instabilities, despite energy dissipation in Ekman layers.

(4) As mentioned above, the appearance of bottom anticyclonic vortices precedes instabilities of the upper cyclonic flow. An interesting outcome of this interaction is the formation of stable, hetroclinic vortex pairs, staggered one above the other. The interface between the layers carrying these vortices of opposite sign domes upward and the vortex pairs translate slowly in the background. They were identified as having close similarities to the structures known as "hetons."

(5) Because of the interest of applying our results to geophysical convection problems, ranging from small hydrothermal plumes with source diameters as small as tens of centimeters to deep convective processes with scales of the order tens of kilometers, the experiments were extended to include finite diameter (d_0) effects of the plume source. It was found that the

point-plume approximation describes the flow fairly well, after the plume descends to depths greater than about $12d_0$.

Some Aspects of the Decay of Convective Turbulence

The decay of temperature and velocity fluctuations in a convective turbulent boundary layer over a heated surface in response to cooling at the surface was studied using a laboratory experiment. The time scale associated with cooling was greater than the relaxation time scale of turbulence, whereupon the convective layer responds to the changes of thermal forcing in a series of quasi-stationary steps. It was found that, when the cooling rate $|dT_s/dt|$ was maintained constant, the decay times of turbulent velocity and temperature fields, from the initiation of cooling, scale with $\Delta T_o/|dT_s/dt|$, where ΔT_o is the temperature difference between the surface and the mixed layer, irrespective of the Prandtl number. Mechanistic explanations were provided to describe the experimental observations. Geophysical relevance of the results was placed in the context of the deep-ocean convection and the atmospheric convective boundary layer.

Turbulent Convection in Rotating and Stratified Fluids

Turbulent convection induced by heating the bottom boundary of a wide, linearly (temperature) stratified, rotating fluid layer was studied using a series of laboratory experiments. It was shown that the growth of the convective mixed-layer is dynamically affected by background rotation (or Coriolis forces) when the parameter $R = (h^2/\Omega^3/q_0)^{2/3}$ exceeds a critical value, R_1, which is approximately 100. Here h is the depth of the convective layer, Ω is the rate of rotation and q_0 is the buoyancy flux at the bottom boundary. When $R > R_2$, where R_2 is approximately 300, the buoyancy gradient in the mixed-layer was profoundly affected by background rotation. Conversely, when $R < R_2$, the buoyancy gradient in the convective layer is independent of the rate of rotation and approaches that of convection in non-rotating fluids. When $R > R_2$, the entrainment velocity was found to be dependent on the buoyancy frequency of the overlying stratified layer, the rate of rotation and the conventional (Deardorff) convection velocity. A simple theoretical formulation for the rate of entrainment was derived, which was found to be in good

agreement with the experimental results. The experimental results also indicate that entrainment in this case is dominated by non-penetrative convection.

The Transition from Density-Driven to Wave-Dominated Isolated Flow

An isolated fluid mass travelling horizontally in a stratified layer is a phenomenon that resembles both a detached gravity-current head and a strongly nonlinear solitary wave. Using laboratory experiments, we examined the transition in time form a regime in which the flow is density driven, to one in which it is wave dominated. A simple means of creating an isolated flow that exhibits both density and wave effects was achieved by dropping a thermal into a linearly stratified layer. This transitional regime is called an 'isolated propagating flow'. Scaling were developed that identify parameters for which the transitional regime occurs. Particle-tracking studies revealed the vertical flow structure. There was an upper zone that is wave- dynamical, and a lower zone in which transport of mass occurred. The transported mass slowly leaked out, until the phenomenon resembles a weakly nonlinear solitary wave. In the ocean, cracks in the ice cap (polar leads) cause similar flows impacting the thermocline.

Ice Formation due to Surface Freezing of a Two-Layer Fluid

A series of experiments aimed at understanding the processes associated with surface freezing of a two-layer fluid was carried out in a laboratory tank. The flow configuration consists of a layer of cold, salty water overlaying a relatively deep bottom layer of warm, saltier water. This situation is common in high-latitude oceans during periods of rapid ice formation. The experiments were conducted in a tank with well-insulated side and bottom walls, placed in a walk-in freezer with air temperatures from -12 to -20 ^{o}C. A system of thermocouples was used to measure the temperatures at fixed levels in water, ice and air. Microscale conductivity and temperature probes were used to obtain vertical profiles of temperature and salinity in water. In general, when external fluxes of heat and salt are absent, such a system enhances static stability, in the sense that the net density difference between the layers increases with time. When external fluxes of heat (because of surface cooling) and salt (rejected during ice formation) are applied,

however, this fluid system may become unstable and overturning of fluid layers is possible. In addition, heat transport from the warmer bottom layer to the colder upper layer may be important, possibly leading to the reduction in the rate of ice formation compared to that of a homogeneous fluid with temperature and salinity identical to the upper layer. Descriptions of such physical processes were advanced using laboratory experiments, and quantitative measurements of salient parameters were compared with the predictions of a theoretical model developed to explicate the flow evolution.

List of Publications

Journal Papers

Noh, Y. and Fernando, H.J.S., "Onset of Stratification in the Mixed Layer Subjected to a Stabilizing Buoyancy Flux," *Journal of Fluid Mechanics,* **304**, 27-46, 1996.

Ching, C.Y., Fernando, H.J.S., Mofor, L. and Davies, P.A., "Interaction of Multiple Line Plumes in an Uniform Environment," *Journal of Physical Oceanography,* **26(4)**, 525-540, 1996.

Fernando, H.J.S. and Hunt, J.C.R., "Some Aspects of Turbulence and Mixing in Stably Stratified Layers," *Dynamics of Atmospheres and Oceans*, **23**, 55-61, 1996.

Kit, E., Strang, E. and Fernando, H.J.S., "Measurement of Turbulence Near Shear-Free Density Interfaces," *Journal of Fluid Mechanics,* **334**, 293-314, 1997.

Fernando, H.J.S. and Hunt, J.C.R., "Turbulent Mixing Across Shear-Free Density Interfaces; Part 1 - Modeling Considerations," *Journal of Fluid Mechanics,* **347**, 197-234, 1997.

Cole, G. and Fernando, H.J.S., "Decay of Turbulent Fluctuations in a Convecting Boundary Layer," *Fluid Dynamics Research* , **23(3)**, 161-176, 1998.

Manasseh, R., Ching, C.Y. and Fernando, H.J.S. "The Transition from Wave-Dominated to Density Driven Isolated Flows," *Journal of Fluid Mechanics,* **361**, 253-274, 1998.

Colomer, J., Zieren, L.D. and Fernando, H.J.S., "Comments on the Paper "Localized Convection in Rotating Stratified Fluid," *Journal of Geophysical Research,* **103(C6)**, 12,891-12,894, 1998.

Fernando, H.J.S., Chen, R-r. and Ayotte, B.A., "Development of a Point Plume in the Presence of Background Rotation," *Physics of Fluids*, **10(9)**, 2369-2383, 1998.

Fonseka, S.V., Fernando, H.J.S. and van Heijst, G.J.F., "The Evolution of an Isolated Turbulent Region in a Stratified Fluid," *Journal of Geophysical Research* (accepted for publication).

Voropayev, S. and Fernando, H.J.S., "On Surface Freezing of Stratified Sea Water," *Journal of Fluid Mechanics* (accepted for publication).

Archival Journal Papers Submitted

Fernando, H.J.S. and Buhler, J., "The Scales of Sediment Fingers," *Journal of Marine Research* (under revision).

Cuprek, J. and Fernando, H.J.S. "Experiments on Doming Isopycnals by an Upward Suction Velocity," submitted for publication..

Boubnov B.M. and Fernando H.J.S., "Experimental Study of Convection from Isolated Source of Buoyancy," Submitted (in Russian) to Izvestia, Fluid Gas Mechanics

Boubnov B.M. and Fernando H.J.S., "Regimes of Convection from a Local Source of Buoyancy in Rotating Fluids," Submitted (in Russian) to Izvestia, Atmospheric and Ocean Physics.

Boubnov B.M. and Fernando H.J.S., "Convection from a Local Source of Buoyancy," Submitted (in Russian) to Dokl. RAS (Proceedings RAS)

Conference Proceedings

Kit, E., Fernando, H.J.S. and Ching, C.Y., Frequency spectra of scalar and velocity fluctuations at entraining stratified interfaces," Sixth European Turbulence Conference, Lusanne; In: Advances in Turbulence VI, Eds. S. Savrilakis, L. Machiels and P.A. Monkewitz, Kluwer Academic Publishers, 595-597, 1996.

Fernando, H.J.S., "Discussion on the Paper, Conductivity Measurements in the Wake of Submerged Bodies in Density Stratified Media," Twenty-First Symposium on Naval Hydrodynamics, June 24-28, Norwegian University of Science & Technology, Trondheim, 1996.

Fernando, H.J.S., Peeters, P., Robles, A. and Niestadt, B. "Laboratory Modeling of Microbursts," 1st AIAA Theoretical Fluid Mechanics Meeting, June 17-20, New Orleans, AIAA Paper 96-2149, 1996.

Kit, E., Fernando, H.J.S. and Strang, E. "Measurement of Zero-Mean-Shear Turbulence in Homogeneous and Two-Layer Fluids," Second International Symposium on Hydrodynamics, Hong Kong, Dec., 16-18, In: Hydrodynamics, Theory and Applications (Eds. Chwang, A.T., Lee, J.H.W. and Leung, D.Y.C), 853-858, 1996.

Fernando, H.J.S., Colomer, J. and Boubnov, B. "Laboratory Studies of Convection from Isolated Sources," *Proceedings, Sixth Asian Congress of Fluid Mechanics*, Madras, 857-859, 1997.

Strang, E., Fernando, H.J.S. and Kit, E. "Aspects of Turbulent Mixing at Density Interfaces," Proceedings, Fifth IMA Conference on Stratified Flows - "Mixing and Dispersion in Stably Stratified Flows," Accepted, Oxford University Press, 1997.

Fernando, H.J.S. "Convection in Rotating Fluids and Its Geophysical Relevance," Proceedings of the Konstantin Federov Memorial Symposium, St. Petersburg., UNESCO Volume # x, in Press.

Lozovatsky, I.D. and Fernando, H.J.S. "Turbulence in Stratified Patches on a Shallow Shelf," Proceedings of the Konstantin Federov Memorial Symposium, St. Petersburg., UNESCO Volume # x, in Press.

Conference Presentations

Ching, C.Y. and Fernando, H.J.S. Modeling of Leads as Line Buoyancy Sources, *Am. Geophys. Union, Ocean Sci., EOS,* **76(3)**, 194, 1996

Fernando, H.J.S., "Formation of Density Staircases in Stratified Fluids: A New Mechanism," *Bull. Am. Phys. Soc.* **41(9)**, 1820, 1996.

Lozovatsky, I. D., and H. J. S. Fernando, "Patchiness and Mixing at the Shelf," The Oceanographic Soc. 1996 Meeting, Amsterdam, 1996.

Fernando, H.J.S. "Rotationally Dominated Convective Turbulence and Its Relevance to Convection in Oceans," 29th International Liege Colloquium on Ocean Hydrodynamics.

Fernando, H.J.S. "Modeling of Geophysical Flows," Invited Speaker, Moscow'97 Conference on Stability and Instabilities of Stratified and Rotating Flows," Moscow, 1997.

Fernando, H.J.S. "Laboratory Experiments on Stratified Shear Flows," Keynote Speaker, International Workshop on Mixing in Geophysical Flows, Barcelona, Spain, 1997.

Voropayev, S.I. and Fernando, H.J.S. "Laboratory Experiments on the Surface Freezing of Stratified Salt Water," *Am. Geophys. Union, Ocean Sci., EOS,* **79(1)**, 152, 1998

Fernando, H.J.S., Chen, R-R. and Ayotte, B.A. "Plume Dynamics in Rotating Fluids," *Am. Geophys. Union, Ocean Sci., EOS,* **79(1)**, 184, 1998

Fernando, H.J.S. "Turbulence and Mixing in Environmental Flows," Invited Paper, "Hopkins Conference in Environmental Fluid Mechanics," 8-9, April 2-4, Baltimore, MD 21218, 1998.

Voropayev, S.I and Fernando, H.J.S. "Laboratory Experiments on the Surface Freezing of Stratified Salt Water," 30th International Liege Colloquium on Ocean Hydrodynamics, May 4-8, 56.

Fernando, H.J.S. "Convection in Rotating Fluids and its Relevance to Deep Ocean Convection," Federov Memorial Symposium on Oceanic Fronts and Related Phenomena, May 18-22, St. Petersburg, Russia, 49, 1998.

Fernando, H.J.S. "Stratified Turbulence," Invited Pedagogical Lecture, IUTAM, IAMAS/IUGG, GTP/NCAR Workshop on "Developments in Geophysical Turbulence," Boulder, CO June 16-19, 1998.

Fernando, H.J.S. Entrainment and Mixing in Stably Stratified Flows, Invited Lecture, GTP/NCAR conference on "Observations, Experiments and LES" Boulder, CO Aug. 12-15, 1998.

Fernando & Levy, M. "Convection in Rotating Stratified Fluids," *Bull. Am. Phys. Soc.* **xx(11)**, xxxx, 1998.

Lucas, D.L., Colomer, J., Fernando, H.J.S. and McCulley, J. "Urban Heat Islands: Flow and Temperature Structure," *Bull. Am. Phys. Soc.* **xx(11)**, xxxx, 1998.

Mahalov, A., Berman, N.S., Fernando, H.J.S., Yu, F. and Pardyjak, E. "Stable Layers in the Atmospheric Boundary Layer," *Bull. Am. Phys. Soc.* **xx(11)**, xxxx, 1998.

Fernando, H.J.S. "Laboratory Modeling of Deep Convective Processes," Labrador Sea Deep Convection Meeting, Big Fork, Montana, Sep 9-11, 1988.